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The Marginal Ice Zone (MIZ) is a complex region both acoustically and oceanographically. The presence of the Polar Front associated with the East Greenland Current causes substantial temporal and geographic variability. In addition, changing combinations of ice cover and open water produces complex range-dependent environments for the propagation of sound at all but the very lowest frequencies. In April and May of 1988, personnel from the Naval Oceanographic and Atmospheric Research Laboratory (NOARL) used the USCGC NORTHWIND to establish an ice camp in the MIZ between Greenland and Svalbard in the Fram Strait, and conduct an environmental acoustic experiment. A comprehensive set of environmental measurements were made that included expendable bathythermographs, conductivity-temperature depth profiles, both vertical and time series, current meter casts, meteorological and navigational measurements, and satellite imagery. Presented here are statistical analyses of oceanographic temporal and spatial variations associated with the Marginal Ice Zone. Additionally, acoustic modeling was used with these data inputs to make propagation predictions at 24, 115, 273, and 200 Hz. The effects of these oceanographic variations on predicted transmission loss are discussed.

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MARGINAL ICE ZONE OCEANOGRAPHIC VARIABILITY AND ITS EFFECTS ON ACOUSTIC PROPAGATION

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ABSTRACT. The Marginal Ice Zone (MIZ) is a complex region both acoustically and oceanographically. The presence of the Polar Front associated with the East Greenland Current causes substantial temporal and geographic variability. In addition, changing combinations of ice cover and open water produces complex range-dependent environments for the propagation of sound at all but the very lowest frequencies. In April and May of 1988, personnel from the Naval Oceanographic and Atmospheric Research Laboratory (NOARL) used the USCGC NORTHWIND to establish an ice camp in the MIZ between Greenland and Svalbard in the Fram Strait, and conduct an environmental acoustic experiment. A comprehensive set of environmental measurements were made that included expendable bathythermographs, conductivity-temperature depth profiles, both vertical and time series, current meter casts, meteorological and navigational measurements, and satellite imagery. Presented here are statistical analyses of oceanographic temporal and spatial variations associated with the Marginal Ice Zone. Additionally, acoustic modeling was used with these data inputs to make propagation predictions at 24, 115, 273, and 2000 Hz. The effects of these oceanographic variations on predicted transmission loss are discussed.

1. Introduction

The propagation of sound in the Marginal Ice Zone (MIZ) off the eastern coast of Greenland is among the least understood and most complex in the entire Arctic[1,2]. The presence of the Polar Front associated with the East Greenland Current causes substantial variability in sound speed profiles and therefore, in acoustic propagation. In addition, changing combinations of ice cover and open water presents complex environments for acoustic propagation.

The Office of Naval Technology (ONT) sponsored and NOARL conducted environmental acoustics measurements in the MIZ off the northeast coast of Greenland, in the Fram Strait, during the Spring, 1988 from an ice camp supported by the USCGC NORTHWIND. Other participants included the Naval Ocean Systems Center, the Applied Physics Laboratory, University of Washington, Ocean Sensors, Inc., the Navy Polar Oceanographic Center (NPOC), and Patrol Wing Five Detachment. This study focuses on one effect of the physical oceanographic environment in acoustic propagation; namely, changing sound speed profiles. This paper examines

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acoustic propagation along a 70 nmi path (from open water, into the icepack), transverse to the MIZ. Along this path, the depth of the Polar Front increases; nominally at approximately 1 m of depth per kilometer of range. At the Polar Front, the intermingling of the colder, less saline Polar Water and warmer, more saline Atlantic Intermediate Water causes mixing and layering resulting in temporal and spatial fluctuations in the sound speed gradient. These two components create an interesting and unique oceanographic medium in which the acoustic sound speed gradient can change rapidly over short distances and in short time periods. This is the environment we wish to study acoustic transmission loss.

2. Experimental Overview

In April and May of 1988 personnel from the NOARL established an ice camp in the MIZ between Greenland and Svalbard in the Fram Strait, to conduct environmental acoustic propagation experiment. Comprehensive and intense environmental measurements were gathered. These data include expendable bathythermographs, conductivity-temperature-depth (CTD) profiles, both vertical and time series current meter casts, meteorological and navigational measurements, and satellite imagery. Oceanographic data was collected aboard the USCGC NORTHWIND, from NORTHWIND based HH-52 helicopters, and from the ice camp. Navigational fixes and meteorological data collected at the ice camp include wind speed and direction, peak gusts, air temperature, barometric pressure, and solar radiation. In addition, Advanced Very High Resolution Radiometer (AVHRR) satellite imagery was collected to find the extent of regional ice coverage during the exercise. Additional details of the environmental measurements, the sensor calibrations, and preliminary analysis are available in Reference 3.

3. Oceanography

Figure 1 shows the oceanographic environment in the marginal ice zone and is taken from Reference 2. Dominating the circulation in the upper 500 m of the exercise area is the southward flowing East Greenland Current that circulates both Polar Water and below that, water of Atlantic origin termed Atlantic Intermediate Water (AIW). AIW composes most the East Greenland Current transport, and is characterized by temperature and salinity ranges of 0° to 3°C and 34 to 35 ppt and acoustic sound velocities >1445 m/s. It has its origin in the Fram Strait where North flowing Atlantic Water entrained in the West Spitzbergen Current branches to the west, mixes with Polar Water, and returns southward as a subsurface water mass in the East Greenland Current. This water mass has a width of approximately 100 km or less and occurs at depths between 50 and 300 meters.

A surface layer of Polar Water overrides the AIW and originates in the Arctic and flows through Fram Strait along the eastern coast of Greenland. Polar water is characterized by temperatures less than 0°C, salinities between 30 and 34 ppt and acoustic sound speed <1445 m/s. A major oceanographic feature, the Polar Front, lies between the cold, low saline Polar Water and the warm, high salinity Atlantic Water. This front is not vertical, but slopes toward the west as a function of depth. The position of front snakes and curves both horizontally and with depth and eddies are easily formed. This area is very dynamic. Historically, the mean position of this front lies near the 1000 m depth contour and like most fronts, is characterized by the appearance of fine structure— here caused by double diffusion processes and inter-fingering of the two water masses. This frontal variability and the dissimilar water masses on either side of the Polar Front caused large temporal and spatial variability in the acoustic sound

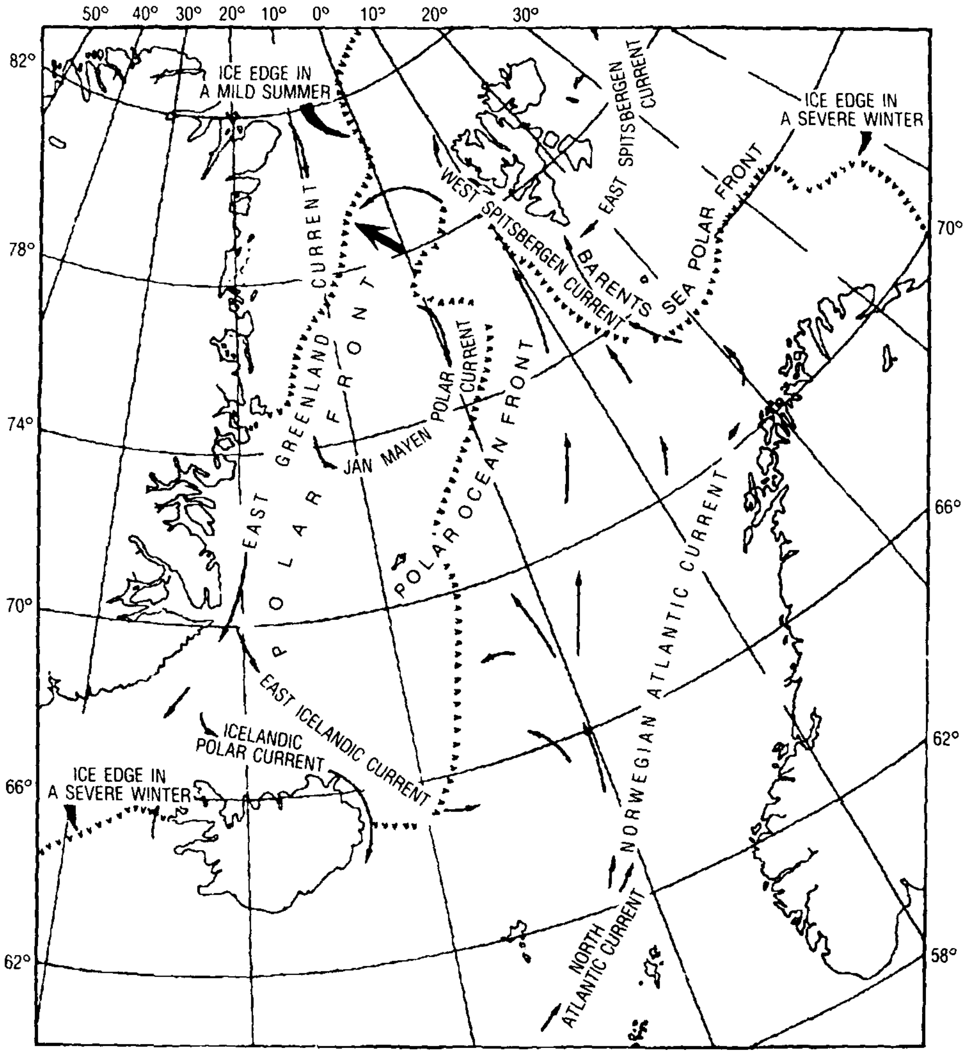

Figure 1. Major currents and oceanographic feature of the East Greenland marginal ice zone, taken from Reference 2.

speed profile during the exercise. The slope of the polar front is not as great as observed elsewhere in the literature since the Polar Front was traversed at an oblique angle.

Figure 2 shows a composite of the six sound speed profiles used for acoustic modeling and the approximate depth of the Polar Front. The range span for each profile is given in Table I, measured from the eastern most profile.

These sound speed profiles are "extended" linearly from 500 m to the bottom, based on water depth. Temperature, and hence sound speed, inversion layers tens of meters thick, are common just below the Polar Front, in the depth range 100-500 m. The nominal sound speed excursion

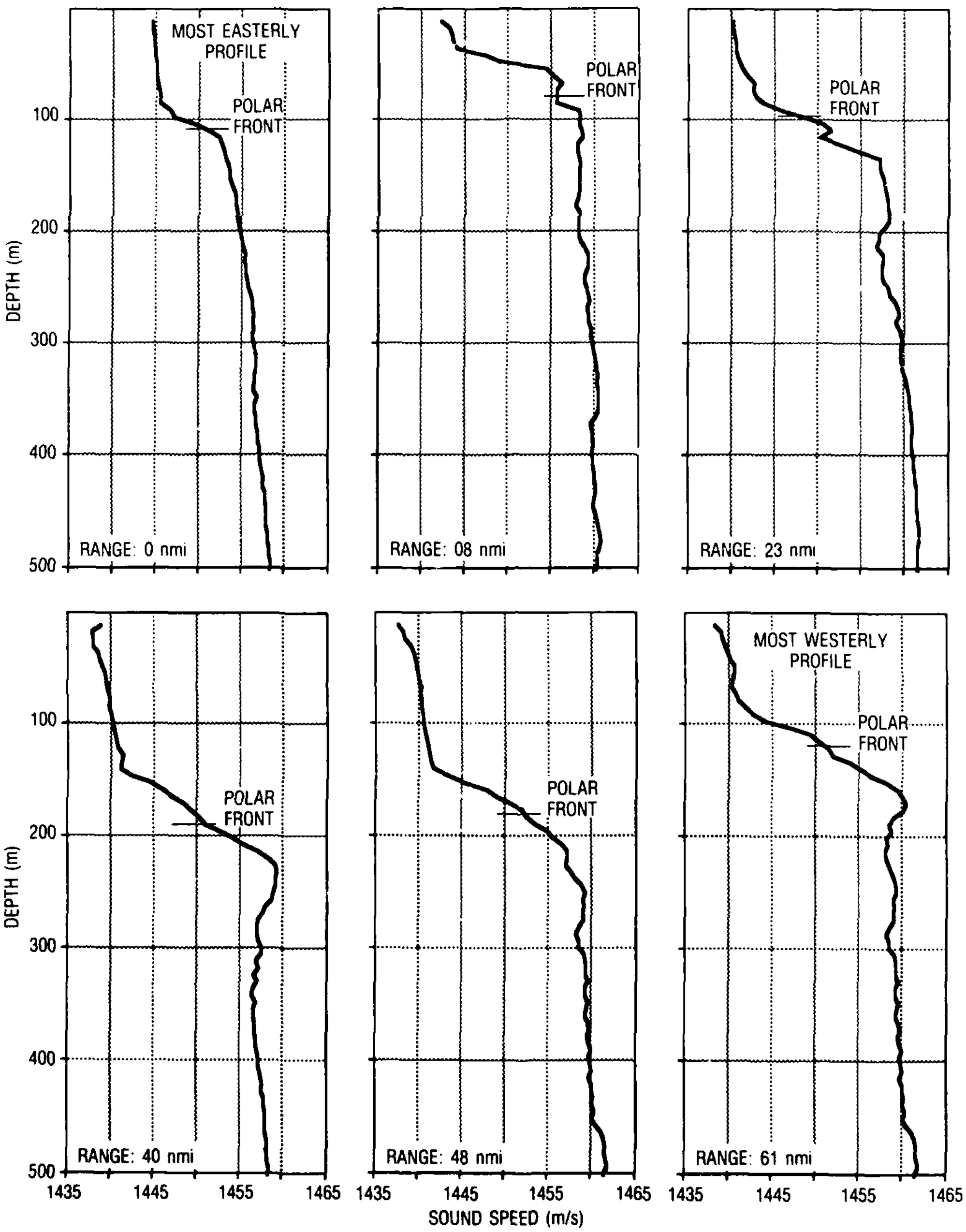

Figure 2. Six sound speed profiles measured transverse to the Polar Front over a range span of 70 nmi. All six are used for the range-dependent acoustic models and only the most easterly is used for the range-independent modeling.

Table I. Range span for each profile used in range-dependent acoustic modeling and the approximate depth of the center of the Polar Front.

OBSERVATION	RANGE FROM EASTERN END OF TRACK (nmi)	POLAR FRONT DEPTH (m)
# 82	0	104
# 83	8	80
# 89	23	104
#109	40	189
#105	48	176
#101	61	115

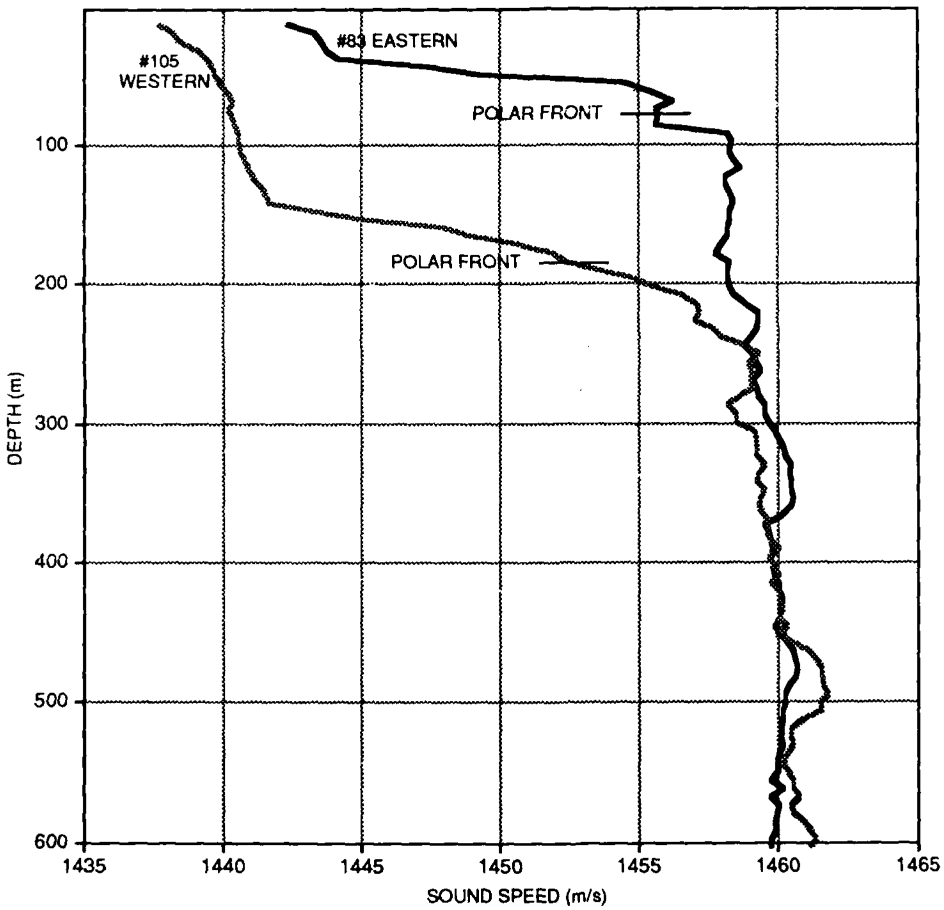

Figure 3. Comparison of the two sound speed profiles taken 40 nmi and 2 days apart to demonstrate sound speed variability.

within any layer is 1.5 m/s. Profile #83 and #105 from Table I are plotted together in Figure 3 to demonstrate the variability in sound speed profiles. These two profiles are separated by 40 nmi and were measured 2 days apart. Depending on depth and range and the position of the Polar

Front, sound speed varies by as much as 15 m/s. Above the front differences of 5 m/s are common and below the front differences average 2.5 m/s. The sound speed gradient, due primarily to temperature, at the interface of the two water masses shows significant spatial variability. Fluctuation of the gradient within each profile increases as the Polar Front approaches the surface and decreases as the front deepens. Significant temporal variability was observed in the sound speed structure and although upcasts are not presented here, marked differences exist between the down and upcasts of the CTDs (a time span of about 30 minutes). Figure 4 shows two pairs of CTDs, all downcasts, and all taken within 24 hours. The first pair, taken 30 minutes apart, and the second pair, taken 60 minutes apart show markedly different sound speeds. Above the Polar Front the sound speed difference averages 0.5 m/s for the 30 minute time span and

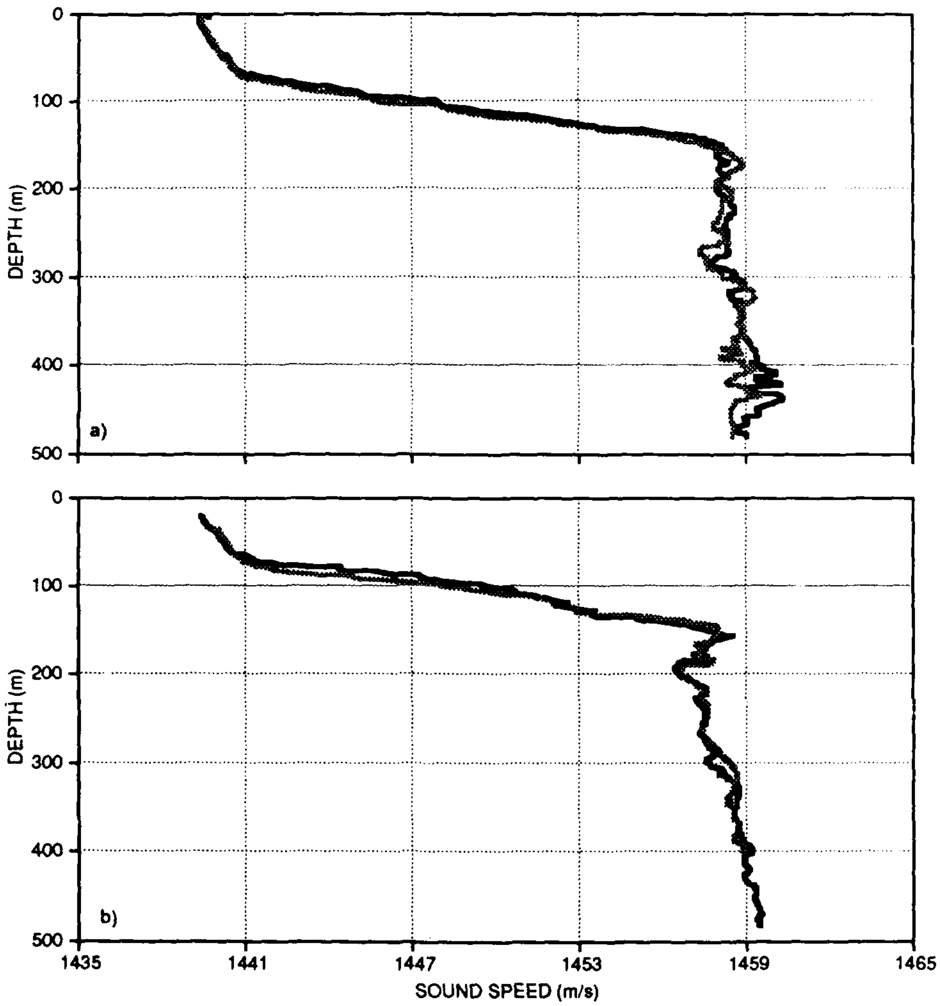

Figure 4. Comparison of sound speed profiles taken a) 30 minutes apart, and b) 60 minutes apart.

5.0 m/s for the 60 minute span. Below the front the differences are 1.5 m/s for the 30 minute span and 2.0 m/s for the 60 minute span. The 30 minute pair seem to zig-zag across each other while the 60 minute pair seem to be offset one from another by about 2 m/s. This tendency causes average differences to be misleading. The 30 minute pair has more zero crossing and thus the average contains more low values near the crossings. The 60 minute pair has less zero crossings and the average represents more of an offset between the two profiles. The 30 minute pair shows more variance below the front than the 60 minute pair, and the 60 minute pair shows a larger difference near the front.

4. Acoustic Modeling

Presented here are comparisons and analysis of modeled acoustic transmission loss for two environmental scenarios; one range dependent; the other range independent. The range-dependent scenario employs six sound speed gradients computed from sound speed profiles in Figure 2. The range-independent environmental scenario uses a single sound speed gradient, the most easterly one used in the range-dependent scenario. For each scenario the acoustic transmission loss is modeled for two source depths, one near and one below the Polar Front. This modeling is needed to support and aid in future processing and interpretation of the experimental acoustic data and is used here to evaluate the effects of changing sound speed on acoustic propagation.

4.1 ACOUSTIC MODELING OVERVIEW

The same bathymetry is used for both scenarios and was obtained from a standard US Navy data base. Acoustic effects due to the spatial distribution of ice coverage were also kept the same for both environmental scenarios. Ice loss was determined from guidelines established in Reference 4 and is the minimum of either a free surface perturbation model or the Gordon-Bucker empirical surface loss model. The ice was modeled as a Gaussian surface with a 4 m RMS roughness and a constant keel spacing of 100 m. Geoacoustic bottom loss parameters were calculated based on the geographic region using a thin sandy-silt layer 50 m thick, a thick layer sediment from 50 – 500 m, and a fully absorbing basement below 500 m.

The two acoustic models used here are from Reference 5. The Split-Step Parabolic Equation (PE) acoustic model is used to make acoustic transmission loss predictions at 24, 115, and 273 Hz. The SSPE uses the Tappert-Hardin split step algorithm and solves the integral solution to the wave equation via a FFT. Time and transform size restrict the use of the SSPE model at frequencies above 300 Hz. ASTRAL, a hybrid acoustic model, incorporates elements of both normal modes and geometric ray acoustics. ASTRAL models propagation at 2000 Hz and assumes adiabatic invariance to propagate mode-like envelopes and obtain acoustic pressure. Comparisons of predicted transmission loss computed from these acoustic propagation models for the two environmental scenarios follows.

4.2 ACOUSTIC MODELING RESULTS

Figure 5 shows acoustic transmission loss predictions vs. horizontal range, at 24 Hz using both a range-dependent and a range-independent environment. Range is measured from the eastern most sound speed profile, westward through the Polar Front. At 24 Hz, there can be significant differences in transmission loss depending on the choice of environmental scenarios. Because both environmental scenarios use the same beginning profile, there are no differences out to a

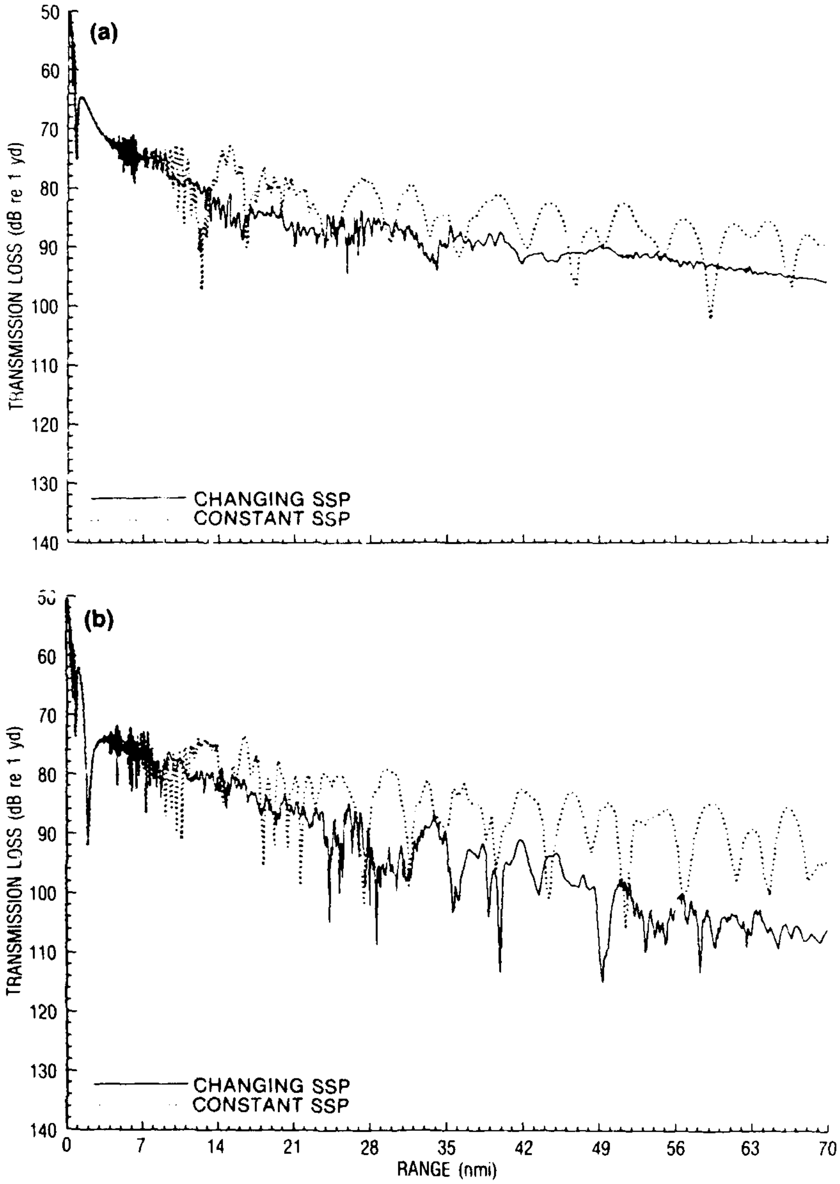

Figure 5. Acoustic transmission loss vs horizontal range, at 24 Hz using both a range-dependent and range-independent environment. Range is measured from the eastern most sound speed profile through the Polar Front. a) Source depth: 130 m, b) source depth: 300 m.

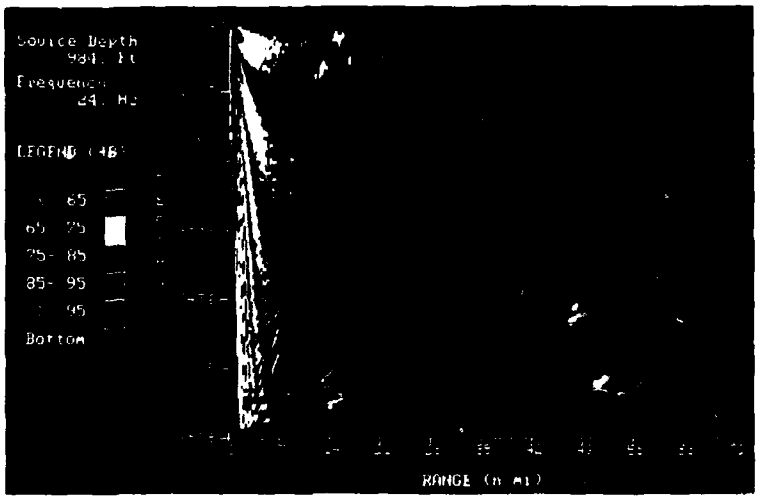

Figure 6. 24 Hz acoustic field intensity vs range for the range-independent scenario with a source depth of 300 m.

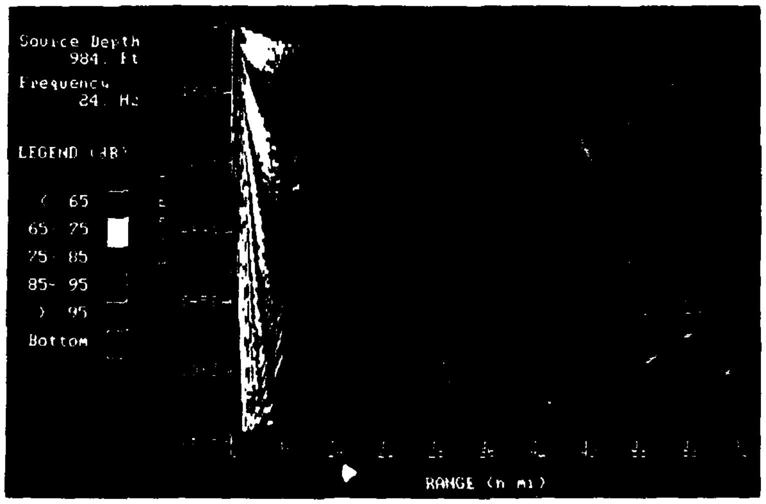

Figure 7. 24 Hz acoustic field intensity vs range for the range-dependent scenario with a source depth of 300 m.

range of 8 nmi, then as the environment changes the differences between the two scenarios become apparent. TL differences between the two scenarios reach 6 dB by 20 nmi and beyond 50 nmi, 15 dB differences appear constant. When compared to the range-dependent scenario, the range-independent scenario shows more structure in transmission loss levels and characteristic deep nulls at a relatively constant range spacing. This is due to the smooth structure of the easterly sound speed profile that has a rounded knee and no relative minimum below the knee. At shorter ranges, the range-dependent scenario shows less of the characteristic deep nulls and their range spacing and the levels exhibit fewer severe fluctuations. For 24 Hz, using the range-independent scenario, the overall transmission loss level is insensitive to source depth, and although the nulls in the transmission loss shift in range, the null spacings are not affected. For the range-dependent scenario, source depth influences transmission loss level, but only after 30 nmi. Here, the western four sound speed profiles have a relative minimum below the knee creating a duct that traps acoustic energy. The deeper source displays 10 – 12 dB more loss at 70 nmi and loss levels exhibit larger and more frequent level fluctuations.

Figure 6 shows the modeled acoustic field intensity vs. range, at 24 Hz, for the range-independent environmental scenario. Figure 7 is the same for the range-dependent scenario. These two figures illustrate how much the range-independent scenario overestimates the acoustic propagation. The differences at the greater ranges and depths emphasize the effects of the range-dependent sound speed profiles.

Figure 8 is similar to Figure 5 for 115 Hz. This and the remaining higher frequencies, show significantly increased TL structure and variability, up to 20 dB. Because of the increased

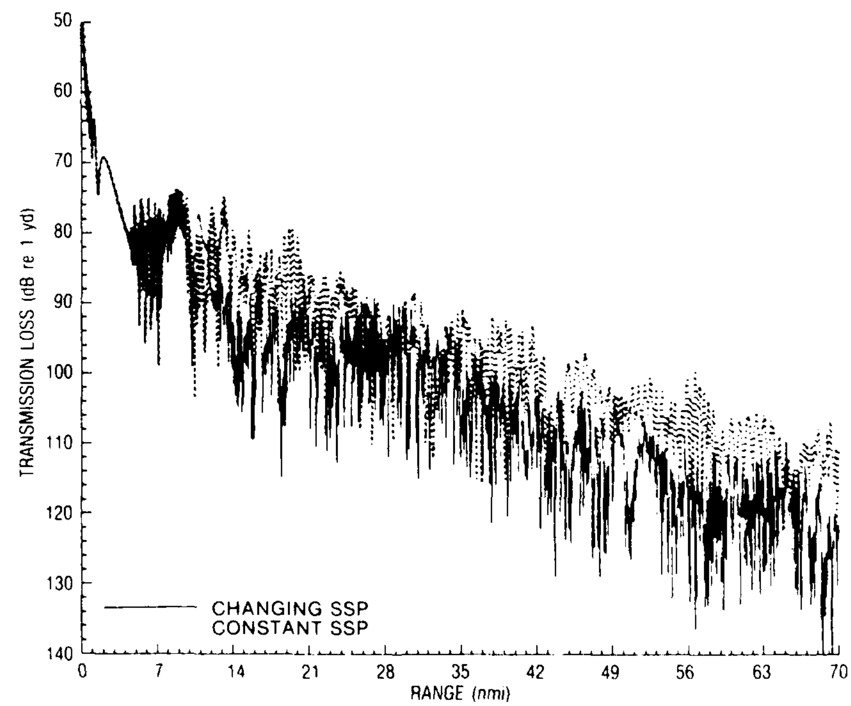

Figure 8. Acoustic transmission loss vs range at 115 Hz showing increased TL level structure and variability, up to 20 dB. Because of this variability subsequent TL levels are averaged over a 0.5 nmi range span to estimate TL differences between the environmental scenarios.

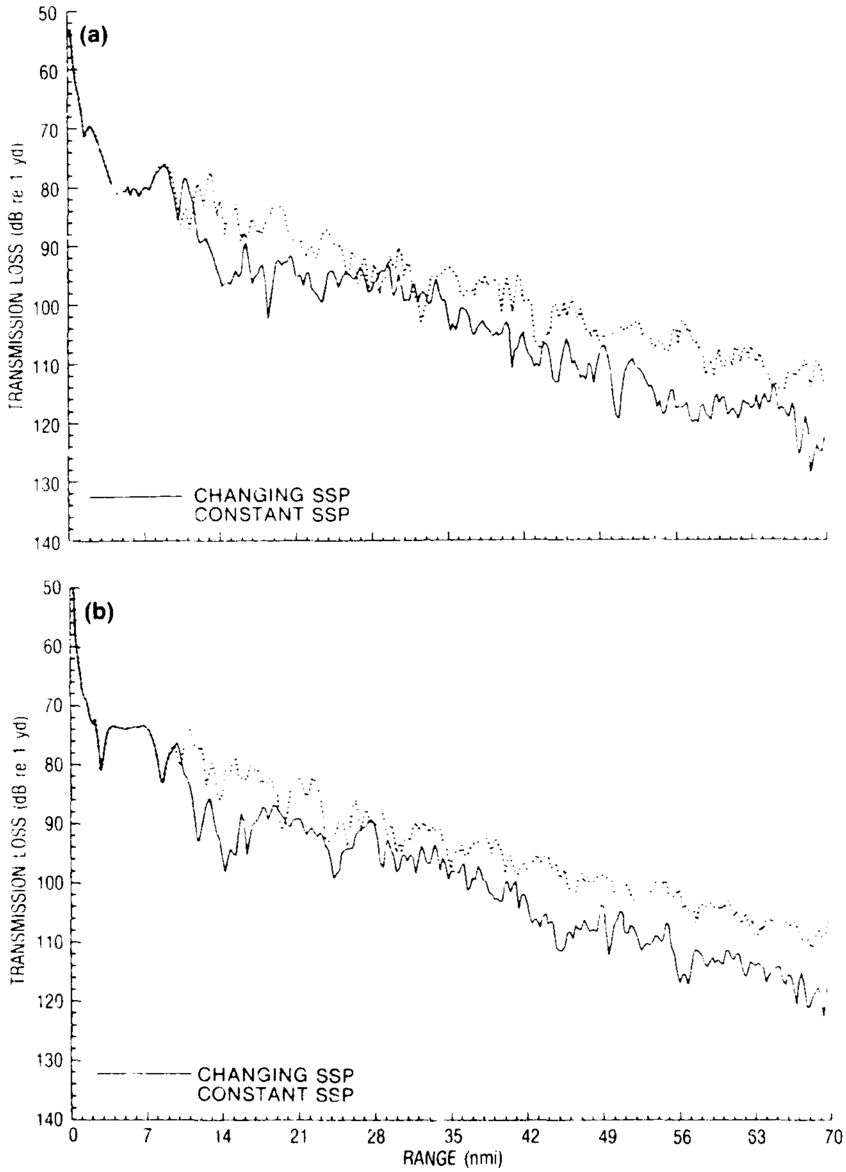

Figure 9. Averaged acoustic transmission loss vs horizontal range, at 115 Hz using both a range-dependent and range-independent environment. a) Source depth: 130 m, b) source depth: 300 m.

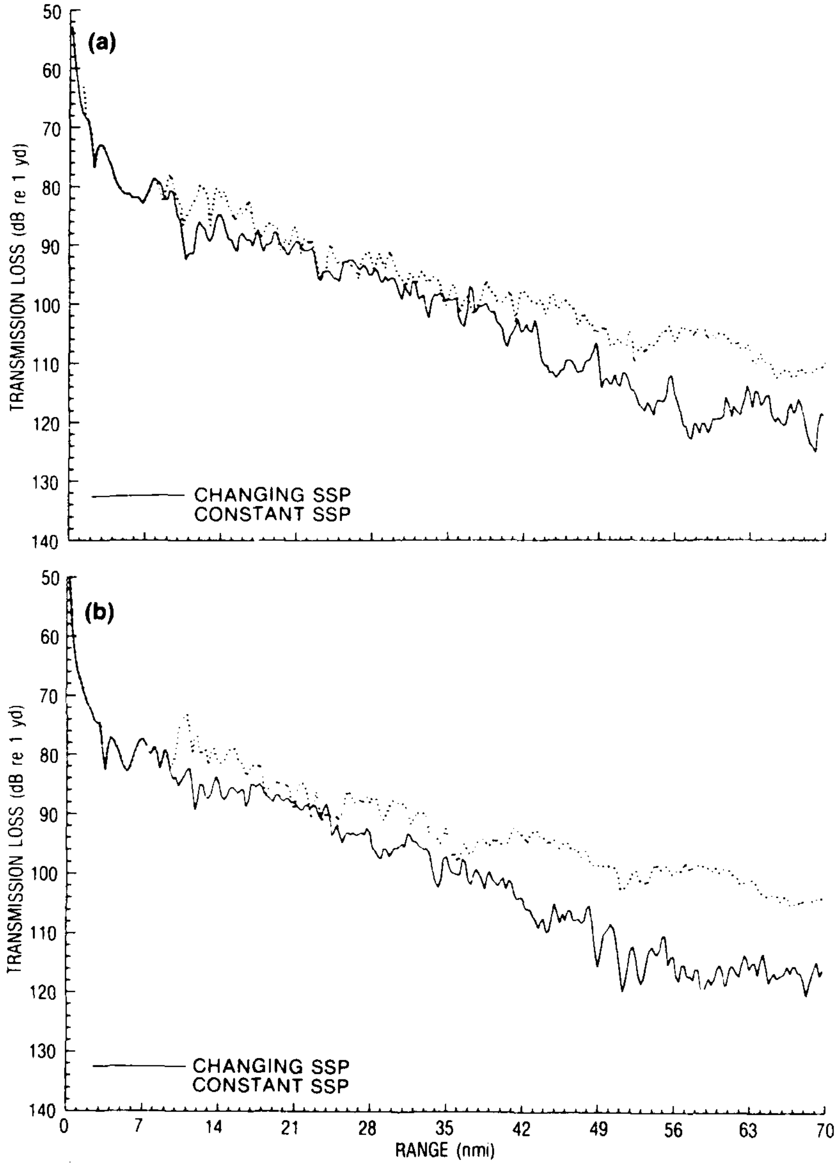

Figure 10. Averaged acoustic transmission loss vs horizontal range, at 273 Hz using both a range-dependent and range-independent environment. a) Source depth: 130 m, b) source depth: 300 m.

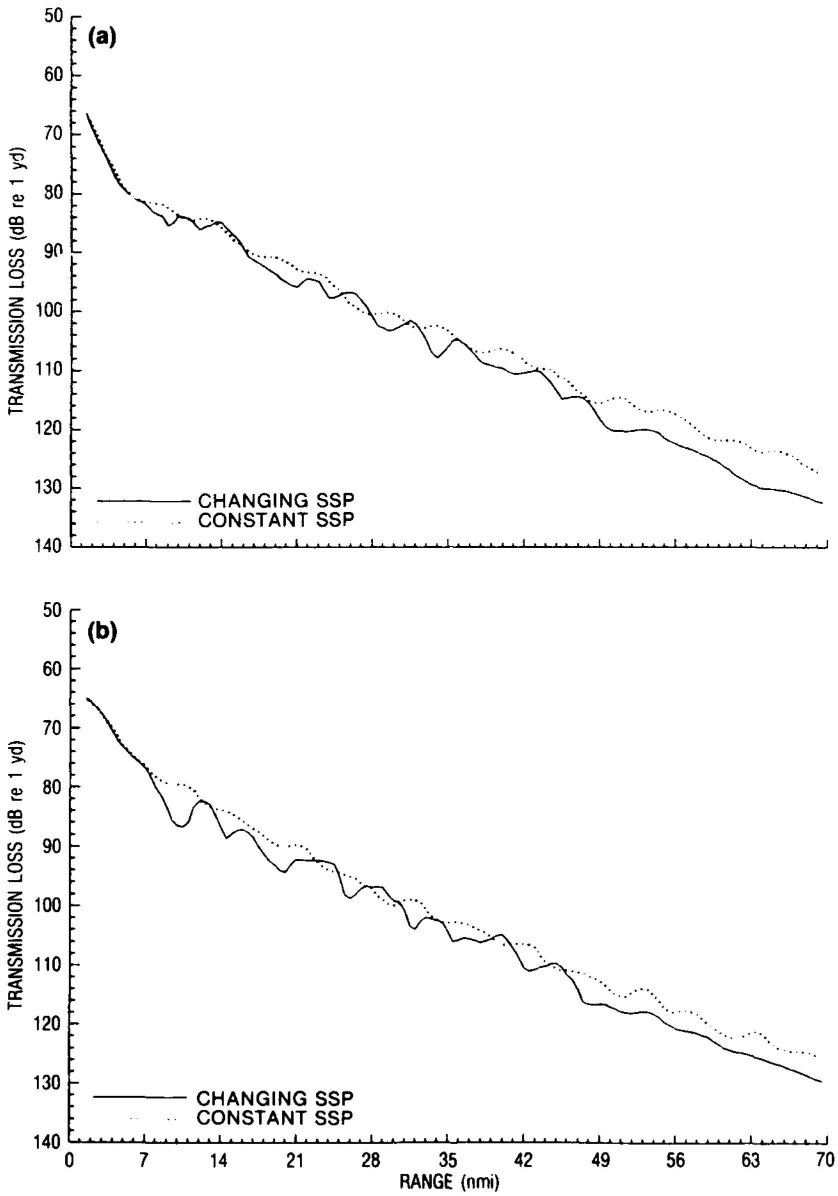

Figure 11. Averaged acoustic transmission loss vs horizontal range, at 2000 Hz using both a range-dependent and range-independent environment. a) Source depth: 130 m, b) source depth: 300 m.

structure in TL levels for these frequencies, levels are range averaged over 0.5 nmi to better estimate TL differences between the environmental scenarios. Figures 9-11 are modeled TL results for 115, 273, and 2000 Hz. At these higher frequencies, no source depth effects were observed for either environmental scenario. Table II summarizes typical differences in the two scenarios for frequency, source depth, and range.

Table II. Transmission loss summary. TL difference is the range-dependent modeled TL minus the range-independent modeled TL.

FREQUENCY/ WAVELENGTH (Hz) (m)	SOURCE DEPTH (m)	TRANSMISSION LOSS DIFFERENCE (dB) HORIZONTAL RANGE (nmi) 14	28	48
24 (60.5)	130	4	5	6
	300	4	7	11
115 (12.6)	130	6	5	8
	300	6	2	8
273 (5.3)	130	2	1	2
	300	2	6	6
2000 (0.7)	130	2	2	2
	300	2	2	2

These results show that the environmental scenario used to analyze the experimental data is important and that a constant sound speed should not be assumed over a 70 nmi range. The range-dependent scenario always gives a higher loss and this additional loss increases with horizontal range and frequency up through 273 Hz. At 2000 Hz there is an average 2 dB difference in TL for the two scenarios at both source depths. At these frequencies, over the 70 nmi range span, the acoustic propagation is dominated more by surface and bottom interaction than by changing sound speed profiles.

Summary and Conclusions

Acoustic modeling results have been presented for both range-independent and range-dependent sound speed scenarios. These results prove that the environmental modeling is important to analyze the MIZ experimental data and that a constant sound speed cannot be assumed over a 70 nmi range transverse to the Polar Front. Sound speed profiles change quickly and significantly over short time periods as well and these changes impact on acoustic transmission loss at low frequencies and over long ranges. Transmission loss (TL) differences between the two environmental scenarios varies from 2 – 12 dB. The range-dependent model always gives higher TL than range-independent model. At 2000 Hz, the difference between the range-dependent model and the range-independent model is a constant 2 dB because sound speed fluctuations are negligible compared to the losses due to the effects of bottom and surface interactions.

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